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SHORT-TERM AGING OF NeFeB MAGNETS FOR STIRLING LINEAR ALTERNATOR APPLICATIONS

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Summary

NeFeB type magnets have been proposed for use in free piston Stirling engine driven, linear alternators to generate electric power during long duration space missions. These type of materials provide the highest energy product commercial magnets, thus minimizing alternator size or mass, but do not provide the high temperature stability of magnetic properties found in the SmCo type magnets. Therefore, to apply the NeFeB type magnets at elevated temperatures to multiyear space missions, their long-term aging characteristics must be determined.

This report presents 200 hour aging data for 6 types of NeFeB magnets selected from 3 manufacturers. Aging was performed under vacuum at 150 C, with a steady demagnetizing field of 5 kOe applied. From the data produced by this short-term aging run, candidate magnet types were selected for a planned 12,000 hour long-term run. Depending on the manufacturer's magnet type, remanence losses observed ranged from 0 to 7%, when measured at 120 C on an established recoil line. Also, intrinsic coercivity losses up to about 4% were observed for the M-H curve at 120 C. In some cases, these coercivity losses were not recoverable by recharge of the magnet, indicating a structural change of the material.

Need for Permanent Magnet Aging Data

To date, the highest permanent magnet energy products, $(BH)_{max}$, have been achieved in magnet materials based on the elements neodymium, iron and boron. A variety of commercial magnets is available in this class, differing in magnetic properties such as remanence (B_r), intrinsic coercivity ($_MH_C$) and temperature capability. These variations are achieved by the addition of other elements, together with generally proprietary processing steps. Hence the magnets can be identified only as belonging to the NeFeB class and the manufacturer's specific designation.

It is well known that the NeFeB type magnets do not have the high temperature stability of magnetic properties possessed by the SmCo type magnets, which can operate reliably at 300 C, or even higher. Therefore, to take advantage of the high energy product (equivalent to a high B_r for a flat topped M-H curve in the 2nd quadrant) of the NeFeB type magnets at elevated temperatures in long duration space travel applications, the long-term aging characteristics of these magnets must be known. Unfortunately, neither long-term (order of years) nor even short-term (a few hundred hours) magnet aging data is readily available for the commercial magnets.

Final aging data to qualify a magnet type for a long term mission has to be taken long term itself and under bias conditions of temperature and demagnetizing field at least as severe as expected in the application. No reliable and inclusive formula for accelerated aging can be given, due to the possibility of multiple aging mechanisms having various activation thresholds. The short-term tests described below were done to preselect 2 or 3 NeFeB magnet types from several manufacturers as the ones most likely to give the best performance in a multi thousand hour aging run.

Magnet Selection for the Short-Term Aging Run

Two types of anisotropic, NeFeB magnet were selected from each of 3 manufacturers:

Vacuum Schmeltze (VAC):	383HR, 396HR
Ugimag:	38KC2, 40HC2
Magnequench:	MQ3-F36, MQ3-F42.

The magnet selection criteria were primarily B_r and ${}_MH_C$. A B_r below 1.2 T at 21 C was deemed to be uninteresting, as 1.2 T is not much above the B_r of some SmCo type magnets. Likewise, an ${}_MH_C$ below about 17 kOe at 21 C was thought to be too low to provide adequate coercivity safety margin at around 100 C. Due to an inverse relationship between B_r and ${}_MH_C$, these criteria greatly delimit the candidate materials.

To fill the 10 available sample slots of the aging fixture, 2 samples of each of the 2 Ugimag and 2 Magnequench types and only one sample of each of the 2 VAC types were selected. The VAC type 396HR was not favored due to a relatively low B_r and the VAC type 383HR was also less favored due to relatively large steps in the top part of its M-H curve.

Aging Bias Conditions

The following aging bias conditions were chosen for the 200 hour run:

Temperature:	150 C
Demagnetizing field:	5.0 kOe.

A demagnetizing field of about 5 kOe was shown in a report [1] dealing with permanent magnet excited linear alternator modeling and tuning to be a fairly typical value. Moreover, at 150 C, a 5 kOe demagnetizing field is already quite close to the knee of the M-H curve in the 2nd quadrant.

The 150 C aging temperature was chosen somewhat arbitrarily as a value significantly above 120 C to accelerate aging, but still within the manufacturers' data limits for the magnets. The 120 C value was previously picked, again somewhat arbitrarily, as a long-term aging temperature sufficiently above the expected real use temperature (~80 C) of the magnets to provide an adequate reliability margin. Preliminary aging runs, 120 hours for the two Magnequench samples and 72 hours for the 40HC2, at 120 C and a 6 kOe demagnetizing field showed little or no resolvable aging effects. There is no more rigorous justification for the choice of these bias conditions.

Experimental Setup of the 200-Hour Run

This short-term aging run was performed on 1-cm cubic magnet samples in vacuum and under the above given bias conditions. The magnet aging fixture, which controls the sample temperature and applies a demagnetizing field, held 10 samples between 4-inch diameter, iron-cobalt alloy pole pieces. This fixture held the magnets in fixed positions, distributed over a pole face so as to minimize any intersample field interference. The manufacturer of this fixture, KJS Associates of Magnetic Instrumentation, Inc., specified the demagnetizing field uniformity to be within 5% over the pole faces. The source of the applied field was a GMW, Inc. 4-inch electromagnet, energized by a Kepco BOP 20-20M bipolar operational power supply. This power supply provided a constant 6.58 A current to the electromagnet, with a stability of better than 1 part in 600 over the period of the run. A 3 part in 500 decrease from the room temperature value of the demagnetizing field was observed, as the electromagnet coils and parts of its frame and poles warmed up during the run, but no correction for this small change was attempted.

The vacuum quality and residual gases in the aging fixture were not well determined. At start, with initialized magnet samples in place, the aging fixture was turbopumped for several days at room temperature. Then the temperature was gradually raised to 120 C, while pumping. After about 2 days at 120 C, the pressure at the turbopump entrance dropped to about $5x10^{-8}$ mm Hg. Clearly, the pressure could have been 10 to 100 times higher in the chamber of the fixture, due to the small pipe leading into the fixture. The prolonged gas load from the fixture may well have come from outgassing at temperature of its Viton o-rings or even from the possibly porous magnet samples, as no helium leak could be detected. Relative to the subsequent aging conditions, this 120 C bakeout was quite harmless, because the magnets then were subjected to a uniform self demagnetizing field of less than 1 kOe.

Magnet Initialization and Measurements

To get meaningful aging data, the magnets need to be "stabilized", or initialized, on a well defined M-H recoil line defined by the bias conditions during aging. It has been shown by machine computation [2] of the self-demagnetizing field of a 1-cm cubic magnet in free space, that at 150 C this field is sufficient to cause local demagnetization of a fully charged sample of the type measured here. However, taking of the M-H curve data requires that a magnet sample be briefly exposed to free space in order to reset electronic integrators. This means that the M-H curve aging data has to be taken at a temperature sufficiently lower to avoid the self-demagnetization danger. This temperature was picked to be 120 C, as it is sufficiently low to avoid the danger and is the same as the temperature of the planned long-term aging runs.

Accordingly, the magnets were initialized at 150 C by repeated application (back and forth on recoil line) of a demagnetizing field up to 5.0 kOe in the aging fixture and then cooled at zero field while still in the fixture. This establishes a recoil line at 150 C. And it also induces corresponding recoil lines, but of unknown field amplitude, at other temperatures. Thus at a lower temperature, a larger demagnetization field can be applied without disturbing the established recoil line. In this way, the B_r on the recoil line could be measured at 120 C, before and after the aging run, to determine the fractional change $\Delta B_r/B_r$.

Measurement of the intrinsic coercivity aging $\Delta_M H_C/_M H_C$ requires taking the full M-H demagnetization curve, which obviously erases the magnetization history. Hence this data curve can only be taken once, at say 120 C.

Experimental Results

The data from the 200-hour aging run at 150 C and −5.0 kOe is reported in Table I. The important magnetization loss data is the decrease in remanence B_r, measured before and after aging on the established recoil line. And the important measure of loss in resistance to demagnetization is the decrease in intrinsic coercivity $_M H_C$, measured before and after aging on the M-H curve. Hence included are the B_r and $_M H_C$ on the initial M-H curve and the B_r and $_M H_C$ on the M-H curve of the sample recharged after aging. A decrease in this latter B_r indicates a permanent loss of magnetic moment due to a metallurgical change. Non-recovery of the full coercivity $_M H_C$ after recharge of an aged sample likewise indicates a basic structural change.

Description of columns in Table I:

1. The remanence B_r before aging, measured on the saturated M-H curve.
2. The remanence B_r before aging, measured on the recoil line.
3. The remanence B_r after aging, measured on the recoil line.
4. The remanence B_r of a sample recharged after aging, measured on the saturated M-H curve.
5. The intrinsic coercivity ${}_MH_C$ before aging, measured on the saturated M-H curve.
6. The intrinsic coercivity ${}_MH_C$ after aging, measured on the M-H curve.
7. The intrinsic coercivity ${}_MH_C$ of a sample recharged after aging, measured on the saturated M-H curve.

Table II presents the fractional aging of the remanence and coercivity, calculated from the data in Table I. The initial B_r and ${}_MH_C$ data is also repeated for reference. It can be seen that many of these fractional losses are at the 1 to 2 percent level, with 1% being close to the resolution limit of the experimental apparatus. Some of the losses are not resolvable from zero.

Description of columns in Table II:

1. The remanence B_r before aging, measured on the saturated M-H curve. Repeats Column (1) of Table I.
2. The remanence B_r before aging, measured on the recoil line. Repeats Column (2) of Table I.
3. Fractional loss of remanence B_r of a sample recharged after aging, measured on the saturated M-H curves. $\Delta B_r \equiv B_{r,\ final} - B_{r,\ initial}$.
4. Fractional loss of remanence B_r, measured on the recoil line. $\Delta B_{r,\ recoil} \equiv B_{r,\ final,\ recoil} - B_{r,\ initial, recoil}$.
5. The intrinsic coercivity ${}_MH_C$ before aging, measured on the saturated M-H curve. Repeats Column (5) of Table I.
6. Fractional loss of intrinsic coercivity ${}_MH_C$. $\Delta_M H_c \equiv {}_MH_{c,\ final} - {}_MH_{c,\ initial}$, where ${}_MH_{c,\ final}$ is measured on the "aged" M-H curve.
7. Fractional loss of intrinsic coercivity ${}_MH_C$. $\Delta_M H_c \equiv {}_MH_{c,\ recharged} - {}_MH_{c,\ initial}$, where ${}_MH_{c,\ recharged}$ is measured on the saturated M-H curve of the sample recharged after aging.

With regard to $\Delta B_r/B_r$ on the recoil line at 120 C, the 10 samples fit into the following groups:

< 1% loss:	396HR, 40HC2
~ 1% loss:	38KC2
≥ 2% loss:	383HR, MQ3-F36, MQ3-F42.

Thus there seems to be a vague inverse correlation between the $(\Delta B_r/B_r)_{recoil}$ at 120 C and the ${}_MH_C$ at 21 C, as inspection of columns 4 and 5 of Table II shows. Only the MQ3-F42 and the 383HR indicated a small (~1%), non-recoverable loss of magnetic moment, which, however, was temperature dependent.

Table II clearly shows a potentially serious, but less discussed phenomenon, namely that the intrinsic coercivity ${}_MH_C$ also ages. On the 120 C aged M-H curve, this loss in coercivity amounted to about 1 to 2 % for all samples except for the MQ3-F42, which suffered a loss over 3%. This loss tended to persist (with altered values) for all samples even after recharge, indicating a structural change that affects domain wall pinning.

Conclusions and Discussion

A first cut at selecting magnet types from the set discussed in this report would be to eliminate both of the Magnequench samples, as they exhibited a 3 to 7 % loss of magnetization when measured at 120 C, after being aged for 200 hours at 150 C, with a 5.0 kOe demagnetizing field applied. The remaining candidates are the two VAC types and the two Ugimag types. The VAC type 396HR seems, however, uninteresting, because its 1.20 T remanence (B_r) at 21 C is the lowest among the samples and not far above that achievable with the more temperature stable SmCo type materials. This pares the candidates down to the VAC 383HR and the Ugimag 40HC2 and 38KC2. At least from the data, the VAC type 383HR does not seem to have anything going in its favor over the Ugimag types. In fact, the 383HR appears to have a twice as high rate of loss of magnetization, compared to the 40HC2 and 38KC2. The remaining 2 magnet types are unfortunately from the same manufacturer. Their loss of remanence was less than 1% and loss of intrinsic coercivity averaged about 2%.

Restriction to just 2 magnet types for the long-term aging run is acceptable, as that allows 5 samples for each type in the present 10-sample aging fixture. Aging more than 2 types simultaneously would make for sparse data for at least one of the types. Sample type distributions such as 2-4-4 or 1-4-5 are of course feasible, but in the group studied here, there is no sample of sufficient interest for the intended application to justify giving it a seat in the fixture.

As observed for the Ugimag samples, the aging data hints at an irreversible increase in top slope and knee rounding of the M-H demagnetization curve. If indeed progressive, this additional effect may lead to accelerated aging such that in the long run the Ugimag materials may lose their initial short-term aging advantage. However, in the proposed schedule for sample testing at 200, 1000, 2000, 6000 and 12000 hours, there is an opportunity to alter sample selection at say the 2000 hour point, with a relatively small loss in time.

References

1. J.M. Niedra, "Lightweight Linear Alternators With and Without Capacitive Tuning", NASA CR-185273, June 1993.

2. Steven M. Geng, private communication, NASA Glenn Research Center.

TABLE I SHORT-TERM MAGNET AGING TEST DATA

Aging environment: Period: 200 hours; Aging temperature: 150 C Demagnetizing H-field: 5.0 kOe;
Recoil line established at 150 C and H_{demag} = 5.0 kOe; X: no data possible.

	(1) B_r initial, (T)	(2) B_r initial, on recoil line, (T)	(3) B_r final, on recoil line, (T)	(4) B_r after recharge, (T)	(5) $_MH_c$ initial, (kOe)	(6) $_MH_c$ final, (kOe)	(7) $_MH_c$ after recharge, (kOe)
VAC							
396 HR (#1)							
21 C	1.20			1.20	25.1	X	24.8
120 C	1.08	1.06	1.06	1.08	10.8	10.75	10.8
150 C	1.02	1.02	X		7.25	X	
383 HR (#2)							
21 C	1.27			1.26	21.1	X	20.8
120 C	1.12	1.10	1.08	1.12	8.50	8.35	8.50
150C	1.08	1.05	X		5.90	X	
UGIMAG:							
40HC2 (#3)							
21 C	1.28			1.28	20.0	X	19.75
120 C	1.16	1.15	1.145	1.16	8.65	8.55	8.65
150 C	1.11	1.09	X		6.15	X	
40HC2 (#4)							
21 C	1.28			1.28	20.1	X	19.8
120 C	1.16	1.15	1.15	1.16	8.75	8.52	8.45
150 C	1.11	1.10	X		6.20	X	

TABLE I CONTINUED

	(1) B_r initial, (T)	(2) B_r initial on recoil line, (T)	(3) B_r final on recoil line, (T)	(4) B_r after recharge, (T)	(5) $_MH_c$ initial, (kOe)	(6) $_MH_c$ final, (kOe)	(7) $_MH_c$ after recharge, (kOe)
UGIMAG							
38KC2 (#5)							
21 C	1.28			1.28	20.5	X	20.2
120 C	1.16	1.15	1.14	1.16	8.75	8.60	8.80
150 C	1.11	1.10	X		6.20	X	
38KC2 (#6)							
21 C	1.28			1.28	20.4	X	20.1
120 C	1.16	1.15	1.14	1.16	8.65	8.50	8.60
150C	1.10	1.10	X		6.08	X	
MAGNEQ.:							
MQ3-F42 (#7)							
21 C	1.30			1.30	17.8	X	17.65
120 C	1.19	1.18	1.125	1.18	8.75	8.45	8.50
150 C	1.14	1.13	X		6.55	X	
MQ3-F42 (#8)							
21 C	1.28			1.28	18.0	X	17.6
120 C	1.17	1.16	1.125	1.16	8.90	8.55	8.55
150 C	1.12	1.10	X		6.60	X	

TABLE I CONCLUDED

	(1) B_r initial, (T)	(2) B_r initial on recoil line, (T)	(3) B_r final on recoil line, (T)	(4) B_r after recharge, (T)	(5) $_MH_c$ initial, (kOe)	(6) $_MH_c$ final, (kOe)	(7) $_MH_c$ after recharge, (kOe)
<u>MAGNEQ.:</u>							
MQ3-F36 (#9)							
21 C	1.26			1.26	17.4	X	17.0
120 C	1.15	1.14	1.06	1.15	8.38	8.25	8.25
150 C	1.11	1.10	X		6.50	X	
MQ3-F36 (#10)							
21 C	1.24			1.24	17.45	X	17.05
120 C	1.13	1.12	1.04	1.13	8.40	8.25	8.35
150 C	1.10	1.08	X		6.75	X	

TABLE II SHORT-TERM MAGNET AGING TEST: REDUCED DATA

Aging environment: Period: 200 hours; Aging temperature: 150 C Demagnetizing H-field: 5.0 kOe;
Recoil line established at 150 C and H_{demag} = 5.0 kOe; X: no data possible.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	B_r initial, (T)	B_r initial on recoil line, (T)	$(\Delta B_r/B_r)$ after recharge	$(\Delta B_r/B_r)_{recoil}$ (on recoil line)	${}_MH_c$ initial, (kOe)	$(\Delta_M H_c/{}_M H_c)$	$(\Delta_M H_c/{}_M H_c)$ after recharge
VAC							
396 HR (#1)							
21 C	1.20		0.00		25.1	X	-0.012
120 C	1.08	1.06	0.00	0.00	10.8	-0.005	0.00
150 C	1.02	1.02		X	7.25	X	
383 HR (#2)							
21 C	1.27	1.23	-0.008	-0.016	21.1	X	-0.014
120 C	1.12	1.10	0.00	-0.018	8.50	-0.018	0.00
150C	1.08	1.05		X	5.90	X	
UGIMAG:							
40HC2 (#3)							
21 C	1.28		0.00		20.0	X	-0.0125
120 C	1.16	1.15	0.00	-0.004	8.65	-0.012	0.00
150 C	1.11	1.09		X	6.15	X	
40HC2 (#4)							
21 C	1.28		0.00		20.1	X	-0.015
120 C	1.16	1.15	0.00	0.00	8.75	-0.026	-0.034
150 C	1.11	1.10		X	6.20	X	

TABLE II CONTINUED

	(1) B_r initial, (T)	(2) B_r initial on recoil line, (T)	(3) $(\Delta B_r/B_r)$ after recharge	(4) $(\Delta B_r/B_r)_{recoil}$ (on recoil line)	(5) $_MH_c$ initial, (kOe)	(6) $(\Delta_M H_c/_M H_c)$	(7) $(\Delta_M H_c/_M H_c)$ after recharge
<u>UGIMAG</u>							
38KC2 (#5)							
21 C	1.28		0.00		20.5	X	-0.015
120 C	1.16	1.15	0.00	-0.0087	8.75	-0.017	+0.006
150 C	1.11	1.10		X	6.20	X	
38KC2 (#6)							
21 C	1.28		0.00		20.4	X	-0.015
120 C	1.16	1.15	0.00	-0.0087	8.65	-0.017	-0.006
150C	1.10	1.10		X	6.08	X	
<u>MAGNEQ.:</u>							
MQ3-F42 (#7)							
21 C	1.30		0.00		17.8	X	-0.008
120 C	1.19	1.18	-0.008	-0.0466	8.75	-0.034	-0.029
150 C	1.14	1.13		X	6.55	X	
MQ3-F42 (#8)							
21 C	1.28		0.00		18.0	X	-0.022
120 C	1.17	1.16	-0.009	-0.030	8.90	-0.039	-0.039
150 C	1.12	1.10		X	6.60	X	

TABLE II CONCLUDED

	(1) B_r initial, (T)	(2) B_r initial on recoil line, (T)	(3) $(\Delta B_r/B_r)$ after recharge	(4) $(\Delta B_r/B_r)_{recoil}$ (on recoil line)	(5) ${}_MH_c$ initial, (kOe)	(6) $(\Delta_M H_c/{}_M H_c)$	(7) $(\Delta_M H_c/{}_M H_c)$ after recharge
MAGNEQ.:							
MQ3-F36 (#9)							
21 C	1.26	1.24	0.00	-0.065	17.4	X	-0.023
120 C	1.15	1.14	0.00	-0.070	8.38	-0.016	-0.016
150 C	1.11	1.10		X	6.50	X	
MQ3-F36 (#10)							
21 C	1.24		0.00		17.45	X	-0.023
120 C	1.13	1.12	0.00	-0.071	8.40	-0.018	-0.006
150 C	1.10	1.08		X	6.75	X	

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NeFeB type magnets have been proposed for use in free piston Stirling engine driven, linear alternators to generate electric power during long duration space missions. These type of materials provide the highest energy product commercial magnets, thus minimizing alternator size or mass, but do not provide the high temperature stability of magnetic properties found in the SmCo type magnets. Therefore, to apply the NeFeB type magnets at elevated temperatures to multiyear space missions, their long-term aging characteristics must be determined. This report presents 200 hr aging data for 6 types of NeFeB magnets selected from 3 manufacturers. Aging was performed under vacuum at 150 °C, with a steady demagnetizing field of 5 kOe applied. From the data produced by this short-term aging run, candidate magnet types were selected for a planned 12 000 hr long-term run. Depending on the manufacturer's magnet type, remanence losses observed ranged from 0 to 7 percent, when measured at 120 °C on an established recoil line. Also, intrinsic coercivity losses up to about 4 percent were observed for the M-H curve at 120 °C. In some cases, these coercivity losses were not recoverable by recharge of the magnet, indicating a structural change of the material.

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